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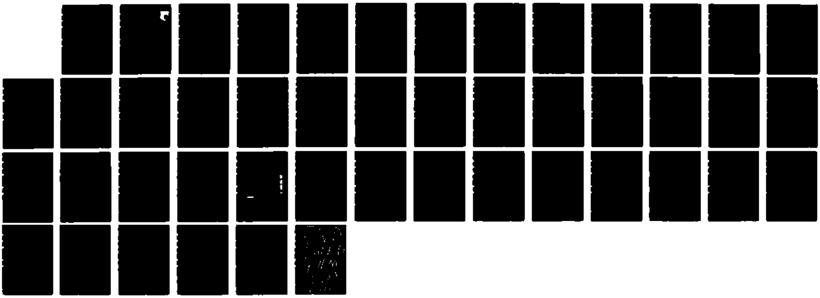

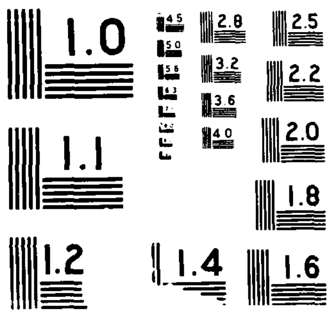
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Volume V

IMPROVEMENT OF HEAD-UP DISPLAY STANDARDS

Volume V: HEAD UP DISPLAY ILS ACCURACY FLIGHT TESTS

Richard L. Newman
Randall E. Bailey
Crew Systems Consultants
PO Box 481
Yellow Springs, OH 45387

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FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6553

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This technical report has been reviewed and is approved for publication.

William L. Augustine
Electronics Engineer
Information Interface Group

Ronald I. Morishige, Lt Col, USAF
Chief, Crew Systems Development Branch

FOR THE COMMANDER

EUGENE A. SMITH, Lt Col, USAF
Chief, Flight Control Division
Flight Dynamics Laboratory

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An in-flight investigation of the effect of head-up display symbol accuracy has been conducted using a variable stability T-33 aircraft. The results indicate that 100-200 ft lateral errors and 500-1500 ft longitudinal errors in locating a contact analog synthetic runway did not cause difficulties for the evaluation pilots. There was no apparent tendency for the subjects to follow HUD cues and ignore real world cues.

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Summary

An in-flight investigation of the effect of head-up display symbol accuracy has been conducted using a variable stability T-33 aircraft. The results indicate that 100-200 ft lateral errors and 500-1500 ft longitudinal errors in locating a contact analog synthetic runway did not cause difficulties for the evaluation pilots. There was no apparent tendency for the subjects to follow HUD cues and ignore real world cues.

Acknowledgement

This design guide was prepared as part of a program to develop new criteria for HUDs. This program had five tasks. Task A was a flight test effort to develop dynamic response criteria for HUD control laws using a variable stability NT-33 aircraft. Task B was a flight test program to determine the accuracy requirements for HUD gyro platforms. Task B was carried out simultaneously with task A. Task C was a simulation study designed to improve symbology for unusual attitude recognition and recovery. Task D was the preparation of a HUD design guide. Task E was a review of HUD safety. This report documents the results of Task B.

The flight tests were performed by Calspan Corporation under subcontract CC-410. Mr. Randall Bailey was the Calspan project engineer for this subcontract. Mr. Louis Knotts was the NT-33 program manager and calibration pilot. This report is an edited version of Calspan Report 7205-14 (Reference 8) with revised conclusions added. Sections II, III, and IV were extracted from the Calspan report. Section V (conclusions) and Section VI (recommendations) represent the opinions of Crew Systems Consultants.

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Abbreviations

AFIFC	Air Force Instrument Flight Center
AFSC	Air Force Systems Command
AGL	Above ground level
AHRS	Attitude heading reference system
ASD	Aeronautical Systems Division
CHPR	Cooper-Harper pilot rating
CRT	Cathode ray tube
DEFT	Display evaluation flight test
DERP	Design eye reference point
EP	Evaluation pilot
FDL	Flight Dynamics Laboratory
FOV	Field-of-view
FPM	Flight path marker (velocity vector)
GPIP	Glidepath intercept point
HUD	Head-up display
ILS	Instrument landing system
IMC	Instrument meteorological conditions
KIAS	Knots, indicated airspeed
LANTIRN	Low altitude navigation and targeting for night
MARS	Mid air retrieval system
MIL	Military (specification)
NASA	National Aeronautics and Space Administration
PIO	Pilot induced oscillation
RAE	Royal Aircraft Establishment
UK	United Kingdom
USAF	United States Air Force
VMC	Visual meteorological conditions

I. INTRODUCTION

The designers of aircraft are rapidly adopting glass cockpit technology where conventional electromechanical and pneumatic instruments are being replaced by cathode ray tubes (CRTs) for presentation of information to the pilot and other crew members. Further, head-up displays (HUD) are being adopted as the primary flight reference for instrument meteorological conditions. This technology influx has created the potential for new and unique formats by which information critical to flight and mission success is conveyed to the flight crew. In fact, single seat, night/all-weather low altitude missions are being flown successfully only because of this technology. The steering group for night attack, as an advisory group for the introduction of LANTIRN (Low Altitude Navigation and Targeting Infrared System for Night), prioritized the head-up display as a critical technological element for this mission(1). In the LANTIRN mission, the flight is conducted essentially with sole reference to the cockpit display environment and the HUD is a critical component. Consequently, the influence of the HUD on flight information processing and manual flight control is critical.

The HUD is an outgrowth of the reflective gunsight of World War II. In such gunsights, the aiming symbol was generated as a collimated beam of light, projected upwards, and reflected toward the pilot by a semi-transparent mirror placed in his field-of-view (FOV) through the windshield. If the design is correct, the pilot will see the symbols floating in his view of the outside scene. The image of the symbols can be focused to form a virtual image which appears to lie in the same plane as the outside visual scene. From lead-computing gunsights, the next step was to place flight information in the virtual image.

The reasons for providing a head-up display are seemingly intuitive:

- A head-up display can reduce pilot workload when the piloting task requires head-up, outside-the-cockpit flight references.

- Improvements in accuracy and efficiency occur from the overlay of HUD-presented data with the external visual scene.

Much of the early development of HUDs took place at the UK's Royal Aircraft Establishment (RAE) in the late 1950s and early 1960s. These early studies indicated that a HUD need not be conformal to the real world, but rather only an approximate overlying of symbols and real world cues was required(2). Part of this may have been the result of a lack of technology to reliably generate a conformal contact analog.

The early work at the RAE was based on extensive flight test and simulator experiments. Most of the conclusions were based on a performance metric, that is, the success criteria for a display was based on the minimum tracking error. The ability of the pilot to monitor the display and his own performance was not usually considered. Naish, in one simulator study, did purposely misguide the subject pilots to a touchdown off the runway(3). He found that the subject pilots tended to ignore the HUD and fly by the real world cues as they became available. Similar experiments were carried out by NASA in the 1970s with similar conclusions.

In two flight experiments, using the mid-air retrieval systems (MARS), pilots tended to believe the HUD cues and ignored the real world cues(4,5). This points out one difficulty with the use of simulators to predict flight behavior. Pilots may well use different strategies when flying a simulated mission than they would in flight.

In the 1980s, the McDonnell-Douglas MD-80 airplane used a HUD as a monitor for the Category II autoland system. The HUD was intended to be used as a monitor, but under some circumstances the HUD would show a perspective runway scene to be used as a control display. Since the MD-80 does not have an inertial navigation system installed, some errors were found in the runway scene. Pilots reported that the display, when mis-aligned caused a strong tendency to steer off of the runway during the landing roll. As a result, the runway display was changed to a much less compelling version(6).

During the 1970s, the USAF installed a modified Sundstrand HUD in a Northrop T-38. This HUD, called the light line, showed a virtual image of the airplane's flight path as an apparent beam of light. Unfortunately, the accuracy of the T-38 heading gyros was such that the lightline HUD did not line up accurately enough with the airplane's actual flight path and the project was terminated(7).

These early results all lead to some fundamental concern about the use of HUDs as flight displays. One question is clearly, how accurate does the airplane's gyro platform have to be? Many military HUD-equipped airplanes have inertial navigation systems which appear to be satisfactory. Other candidate airplanes for HUDs -- transports, trainers, etc. -- do not have inertial navigation capability. For these airplanes, we need to determine the minimum accuracy required for the gyro platform.

From the MD-80 history, it appears that the HUD symbology may affect the answer to this question. A very realistic contact analog display was unacceptable with the heading errors in the MD-80, while a less realistic symbolic runway symbol (the sidelines of a very short, wide runway) was satisfactory.

The present study was designed to address the issue of how accurately does the runway symbol have to be placed to produce an acceptable HUD. To this end, an in-flight experiment was conducted using the USAF variable stability NT-33A aircraft. The NT-33A aircraft is equipped with a programmable head-up display which is part of the Display Evaluation Flight Test (DEFT) system. Two experiments were conducted. One was to investigate the dynamic response requirements of the HUD flight symbols and the second to determine the accuracy requirements for instrument approaches. The two tasks were conducted simultaneously. The dynamic response study has been reported elsewhere(8,9). The accuracy study is the subject of this report.

II. OBJECTIVES

The global objective of this study was to investigate accuracy needs of the pilot when viewing real world cues and HUD cues simultaneously. The head-up display by its nature and format is a compelling instrument. If the HUD symbol and its real world counterpart differ, this must not create problems either from the point of view of the pilot ignoring the HUD because of loss of confidence or, more importantly, ignoring the real world cues because of over-confidence in the HUD or because the HUD creates an illusion that is too compelling.

This task examined various contact analog runway displays for the instrument approach and landing task and also the potential hindrance caused by the display in the transition to visual flight reference. The evaluation included intentional inaccuracies in the proJection of the HUD displayed runway symbology as it appeared to overlay the actual runway. In this manner, the pilot's ability to transition from the HUD to outside-the-cockpit, visual flight reference will be tested under varying degrees of accuracy for which sensors can determine an aircraft's position and attitude.

The landing task was chosen because it is considered to be a significant issue and because it was felt that weapon delivery accuracy would be driven by the weapon accuracy specification.

The objectives of the subject task (symbol accuracy requirements) were:

- Investigate pilot performance and judgment during the IMC/VMC transition from an instrument landing system approach under conditions of HUD symbol inaccuracies.

- Determine if there is any tendency for pilots to follow the HUD and ignore real world cues during the IMC/VMC transition or thereafter.

- Generate pilot opinion ratings and comment data regarding the optimum head-up display for the instrument approach and landing task.

- Examine different runway symbol types and their effect on the instrument-to-visual transition for landing in the face of sensor limitations and errors and, also, in their ability for providing approach guidance information.

III. EXPERIMENT DESIGN

An in-flight investigation of Head-up Display (HUD) symbol accuracy requirements was conducted using the USAF Flight Dynamics Laboratory variable stability NT-33A aircraft. The NT-33A aircraft is an inflight simulator equipped with a programmable head-up-display which is part of the DEFT system. The handling qualities and display characteristics of the inflight simulator can be easily altered for experimentation purposes.

The NT-33 variable stability system capabilities are used to simulate different aircraft handling qualities characteristics for the evaluation pilot who sits in the front seat of the two-seat NT-33. The mechanization of the NT-33 simulation is not unlike a ground-based simulation; however, the NT-33 simulation is essentially unconstrained in motion response and the visual environment is real. The motion of these simulated configurations are sensed by appropriate transducers. These signals are conditioned and processed in the programmable display system of the NT-33 for head-up display presentation. Instrument meteorological conditions (IMC) are effectively and safely simulated by using a blue/amber system. The front canopy of the NT-33A is covered with an amber plastic sheet; when the front seat pilot lowers his blue visor, the complimentary colors produce an almost completely black outside environment. Flight, in this instance, is conducted by the evaluation pilot solely from the cockpit display environment. The simulated aircraft configurations, HUD format, symbols, dynamic response characteristics, and evaluation task were selected are tailored to satisfy the objectives of this experiment.

A. Experiment Variables

This experiment consisted of two tasks: Task A was an investigation of the effect of head-up display symbol dynamic response characteristics on flying qualities; Task B was an investigation of symbol accuracy requirements as they pertain to the accuracy by which a contact analog runway display symbol overlays the real world and the potential hindrance introduce by the HUD in the pilot's transition from instrument-to-visual flight reference. While the two experiments were conducted one the same flight, in reality they were two separate experiments.

The experiment variables for this study were:

- (Intentional) HUD symbology errors,
- Runway display symbol.

With the experiment objectives and variables thus defined, the experiment configurations and mechanization are documented in the following sections.

B. USAF/FDL NT-33A Research Aircraft

The NT-33A aircraft is an extensively modified Lockheed T-33 jet trainer. It is owned by the Flight Dynamics Laboratory and operated under contract by Calspan Corporation. The front seat control system of the NT-33A has been replaced by a full authority fly-by-wire flight control system and a variable response artificial feel system. The evaluation pilot, who sits in the front cockpit, controls the aircraft through a standard centerstick and rudder pedal arrangement or a sidestick controller installed on a right-hand console as an alternate pitch and roll controller.

The front seat, fly-by-wire control system and variable response feel system can be programmed to simulate several aircraft configurations. The system operator in the rear cockpit, who also acts as safety pilot, controls the HUD and aircraft configuration. It is important to note that the evaluation pilot cannot feel the control surface motions due to the actions of the variable stability system signals in the NT-33. During this experiment, the evaluation pilot had no prior knowledge of the configuration characteristics.

Safety features are an essential and integral part of the NT-33 research aircraft. Continuous safety monitors activate an automatic safety trip system to disconnect the evaluation pilot from the fly-by-mire control system before unsafe flight conditions or aircraft attitudes occur. Aircraft control reverts to the safety pilot who occupies the rear seat with unmodified T-33 flight controls. The safety pilot, who also acts as the systems operator, provides an additional, redundant margin of safety by his ability to disengage the variable stability system manually.

Details of the simulation mechanization are provided in References (8 and 10).

C. Head-Up Display (DEFT)

A fully programmable head-up display (HUD) which is part of the display evaluation flight test (DEFT) system is installed in the front cockpit. The DEFT system is described elsewhere(11). Eight distinct display programs are available for loading in flight. Within each program are data stored for six runways for landing and approach evaluations.

The HUD optics, field-of-view, and design eye reference point (DERP) were not experimentally varied nor formally evaluated. These hardware items were the nominal DEFT system and are

unique to the HUD and its installation In the T-33. Unfortunately, the HUD FOV and DERP are not optimal. The instantaneous FOV is limited to approximately 16 deg in azimuth and 18 deg vertical. The DERP is low and hence, a potential hindrance to the pilot. The DERP is restricted because of ejection envelope and panel mounting constraints in the T-33 installation. These deficiencies were noted by all of the evaluation pilots. DERP location and limited FOV problems are typical of many HUD-equipped aircraft.

Instrument meteorological conditions were simulated using a blue/amber system. An amber vinyl plastic sheet covered the inside front half of the NT-33 canopy. Blue snap-on visors were provided to the evaluation pilots. The complementary colors, with the blue visor lowered, effectively present instrument meteorological conditions to the evaluation pilot, yet do not overly restrict the visual conditions of the safety pilot.

The blue-amber system has several advantages over previously tried systems:

- It is, perhaps, the only means of simulating IMC while using a HUD which will retain adequate visibility for the safety pilot.

- The evaluation pilot cannot cheat the visual restriction (such as is possible IMC visors).

- The blue/amber is less cumbersome than canopy drapes.

- The IMC restriction can be quickly and easily removed.

As in any simulation, the blue/amber simulation of instrument conditions is not without its limitations. These imperfections are itemized for proper interpretation of the experiment results:

- The ability to transition quickly from IMC to VMC is a disadvantage as well as advantage of the blue/amber simulation. Night flying instantly can become full daylight VMC. This situation is not completely realistic and some visual accommodation is needed after the transition. The HUD intensity, usually set for night conditions, needs to be increased after the transition to VMC to be legible.

- The blue/amber technique does not provide any shades of gray between full VMC and IMC. Also, the majority of flights were flown in very good weather conditions (always under visual flight rules) and typically good visibility (greater

than 10 miles). During a landing approach evaluation, a somewhat unrealistic situation occurs because the breakout from instrument conditions in the blue/amber simulation yields limitless visibility. Approach, threshold, and runway edge marker lights are absent in this scenario.

Although the IMC simulation was not perfect, it did provide a constant and consistent IMC simulation for which to test head-up display systems.

D. Aircraft Configurations Flown

Two flight phases were flown on each sortie:

- up-and-away (symbol response study)
- power approach and landing(symbol response study and display accuracy study, this study)

Details of the evaluation task, procedures, and flight phase are given in Section IV.

In the power approach flight phase, two fighter and one transport-type aircraft configuration were simulated. The fighters were identified as Configurations D and E, and the transport as Configuration T. For the purposes of this study, the differences were slight. All three were designed to be good, level 1 by MIL-F-8785C, (12) aircraft. Configuration E would be termed slightly sluggish. Details of the aircraft and control dynamics for each configuration can be found in elsewhere(8,9).

E. Head-Up Display Configurations

For this study, intentional misalignments between the real runway and a contact analog HUD runway symbol were introduced. Three different runway symbols were investigated.

A generic head-up display format was used as the baseline display format. This generic HUD format was used to keep display clutter to a minimum. Mission specific information was not programmed nor was it felt to be required. A generic HUD was suitable for our purposes since other tasks under this investigation of HUD requirements were intended to investigate optimal display formats and presentations. The generic HUD format used as the baseline display is sketched in Figure 1.

The primary features of the display are the digital airspeed, altitude, and heading information readout, with a 1-to-1 pitch ladder. The pitch ladder is marked in 5 degree increments; the pitch ladder below the horizon is dashed whereas a solid line

is used for positive pitch attitudes. The ladder tails point to the horizon. Negative signs are not shown. This format is essentially the nominal DEFT system, which is similar in many respects to the presentation used in F-18 aircraft.

The waterline marker is a fixed reference approximately parallel to the aircraft waterline reference. The nominal velocity vector (FPM for flight path marker) was calculated using air mass quantities (i.e., FPM = THETA - ALPHA). When the velocity vector was freed in azimuth, it displayed sideslip. For the majority of the program, a declutter option was available to the pilot. He had the option through a pushbutton on the front seat instrument panel to select either of three presentations of the waterline and velocity vector:

Declutter	(0):	waterline not displayed; velocity vector displayed (caged in azimuth)
	(1):	waterline displayed; velocity vector displayed (free in azimuth)
	(2):	waterline displayed; velocity vector not displayed.

Only air mass velocity vectors were used in this experiment. This was done for two reasons. First, since we would be introducing deliberate errors into the runway, using an inertial velocity vector would show the error to the pilot immediately. If an air mass velocity vector were used, the pilot could not tell from the HUD whether there was an error in the runway or if there was a strong wind.

The second reason was to avoid problems because of the relatively slow (10 Hz) update rate of the inertial velocity vector.

Several display options were evaluated briefly. These included:

- Potential Flight Path Marker

- Angle of Attack Bracket

The potential flight path marker is a display feature adopted from the unique all-analog Klopfstein display (13). The potential flight path marker is, in essence, the rate of change of the flight path. It is indicated by triangular carets at the periphery of the display (Figure 2). The potential flight path markers indicate where, if the controls were left unchanged, the flight path will eventually move. The potential flight path markers can be thought of as thrust/throttle flight directors. When the potential flight path and flight path markers are aligned, thrust equals drag and the aircraft is stabilized on the indicated flight path angle.

The angle of attack bracket display provides an explicit target angle of attack marker for the power approach (Figure 3). The sense of the bracket is fly-to. The bracket shows a deviation of one degree from the target angle of attack. If the angle of attack exceeds the target by greater than 1.2 deg, a digital readout of the angle of attack is presented in the lower left hand corner of the display. The bracket is drawn with respect to the waterline marker.

F. Symbol Accuracy and Display Variables

It was necessary to implement intentional errors in the calculation and hence, display of a contact analog-type approach and landing symbology.

A generic contact analog runway overlay was programmed as the nominal case. This display was created by augmenting the generic HUD format used in the up-and-away flight condition with landing guidance information. For the landing and approach evaluation, a mode logic was implemented. Once the approach mode was initiated, the automatic mode sequencing of DEFT was activated. This sequence was started upon safety pilot activation of the APPROACH mode. Initially, raw ILS data drive deflection needles displayed on the HUD. The needles are split (i.e., glideslope needle separated from the localizer). Distance to the glidepath intercept point with the runway is digitally shown in the lower right-hand corner of the display as a DME readout. The needles are drawn with respect to the velocity vector. Once inside the approach cone, the needles are blanked and a contact analog runway symbol is drawn. Under normal conditions, this symbol would overlay the real-world runway (Figure 4). This symbol is sized to project an area equal to the real runway when viewed from the airplane cockpit. The size, shape, and orientation of this runway symbol changes as the airplane maneuvers for landing to retain the conformal, 1:1 relationship and the proper runway perspective.

The philosophy behind the contact analog, runway landing symbology is that the line-up for landing and transition from inside-the-cockpit instrument to outside-the-cockpit visual flight reference is optimized and simplified. For instance:

- The perspective provided by the runway display is a surrogate to the visual runway landing scene. The pilot's experience and skills in the visual landing task are, consequently, transferred to the instrument approach with the contact analog runway.

- Flight director guidance information is not needed; the pilot, in essence, provides the necessary compensation through his internal thought and visual perception mechanisms as he normally would in a visual landing. The instrument landing task changes from one of flying flight director or ILS needles to the usual task of visual landing.

- The pilot's visual transition from this display to the outside world for landing is dramatically improved. The pilot is presumably focusing significant attention to the runway symbol projection for the HUD; once the instrument conditions abate, the actual runway and visual cues will appear under the HUD runway display.

- The pilot's cross check from head-down to head-up for visual breakout is virtually eliminated. Also, the pilot can focus his attention for breakout indicators (runway lights) in the vicinity of the displayed runway.

Clearly, the contact analog runway provides several important advantages. The contact analog runway, such as the unique all-analog Klopfstein format, has been successfully demonstrated and used. In this program, the runway of the Klopfstein all-analog format has been superimposed on the generic, digital format HUD.

The last bullet highlighting the advantages of a contact analog runway, also points out a potential deficiency of this concept and is, thus, the subject of this task. Visual fixation on the head-up display has been often reported; if there are errors in the framing or display of the runway symbol, can the pilot transition from the HUD to detect these errors in a timely fashion and successfully land the aircraft?

The objective of this task were, thus:

- Investigate pilot judgment and potential hindrance during the transition from the inside-the-cockpit instrument to outside-the-cockpit visual flight reference from an instrument landing approach using a contact analog-type HUD format.

- Examine this transition behavior in the face of errors in the displayed runway projections.

- Examine this transition behavior and manual approach performance using different runway symbols.

Three runway symbols were examined which vary in perspective detail and attractiveness. The three symbols were chosen to span

a range of potential transition hindrance, display attractiveness, and fullness of perspective:

- Runway Symbol A: Full runway outline with centerline projection identical to the Klopfstein runway symbol (Figure 4). This runway symbol is sized to be equal to the actual runway length and width. (This runway symbol was used in the power approach task evaluation in Task 1 of this experiment).

- Runway Symbol B: Sidelines-only display (Figure 5). This runway symbol is a fixed size and represents more of an error box rather than a contact analog runway. It was felt that this display presented less of a potential visual transition hindrance. Rather than being a runway outline, the symbol indicates to the pilot that the runway is somewhere in the general subtended area. This symbol is sized to be equal to a 2000 ft runway 500 ft wide. The same symbol also flown (Symbol B') which was the same length (2000 ft), but only 250 ft wide.

- Runway Symbol C: Centerline only display (Figure 6). This symbol is also a fixed size and marks only the extended centerline and glidepath intercept point (GPIP) threshold. The threshold marker is sized to equal to a runway width of 175 feet.

All of the HUD formats are identical with the exception of the different symbols. The dynamics and techniques associated with the framing of the runway symbols are identical.

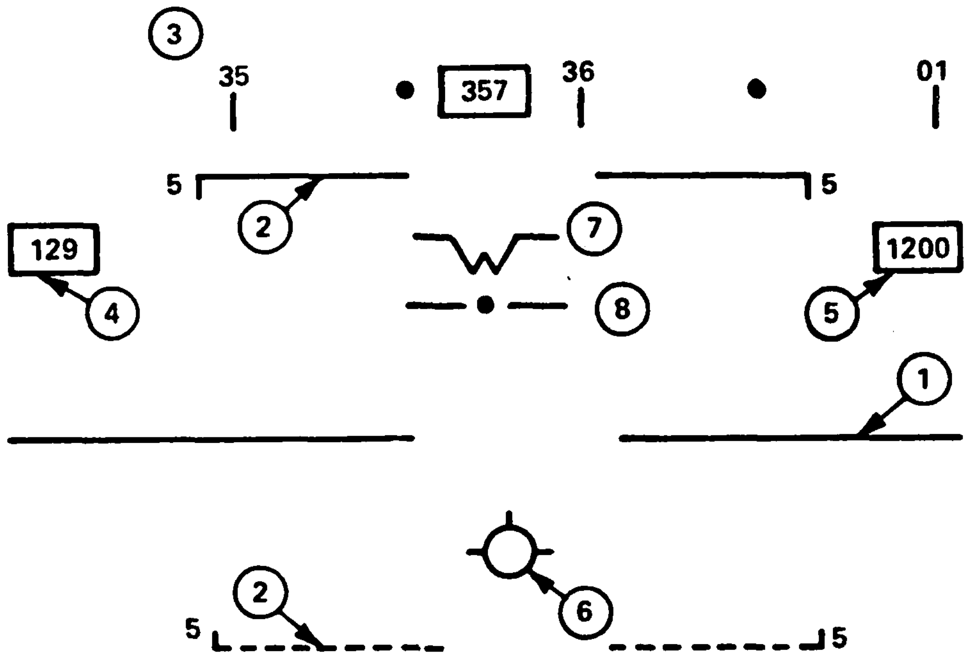
All of the runway symbols are referenced to the glidepath intercept point (GPIP). For instance, with a perfect overlay using Symbol A, the symbol will subtend the runway beginning at the glideslope intercept point and extending to the departure-end threshold. The approach-end runway threshold is not included in the overlay.

Three types of intentional errors were introduced in this experiment. These were lateral offsets, longitudinal offsets, and directional deviations. These are illustrated using Figure 7.

C. Experiment Overview

The primary experiment matrix consisted of:

- Power approach aircraft configurations.
- Constant motion and visual path temporal distortions 180 msec time delay in the pitch motion and 64 msec time delay from motion to head-up display (visual) pitch response).
- Constant velocity vector dynamics.
- Three contact analog-type runway symbols.
- Variations in the accuracy by which the projected runway marker overlaid the real-world runway. The deviations were in the longitudinal (parallel to centerline), lateral (perpendicular to runway centerline), and directional (angular deviations about the glidepath intercept point) directions.



1. HORIZON LINE
2. PITCH LADDER (1:1 PITCH LADDER)
3. HEADING SCALE
4. INDICATED AIRSPEED
5. BAROMETRIC ALTITUDE
6. FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
7. WATERLINE (PITCH MARKER)
8. COMMAND BAR FOR HUD TRACKING TASK (IF SELECTED)

Figure 1

Baseline Display (Generic HUD Format)

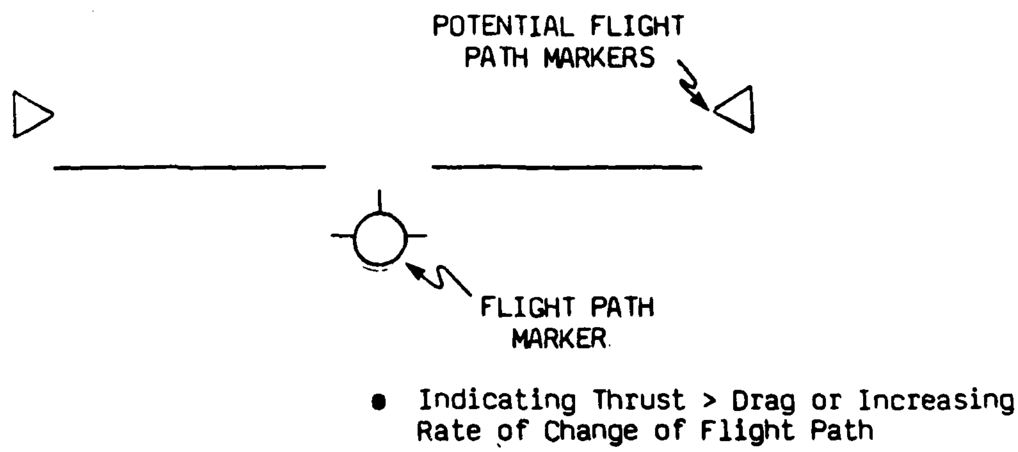


Figure 5

Potential Flight Path Symbol

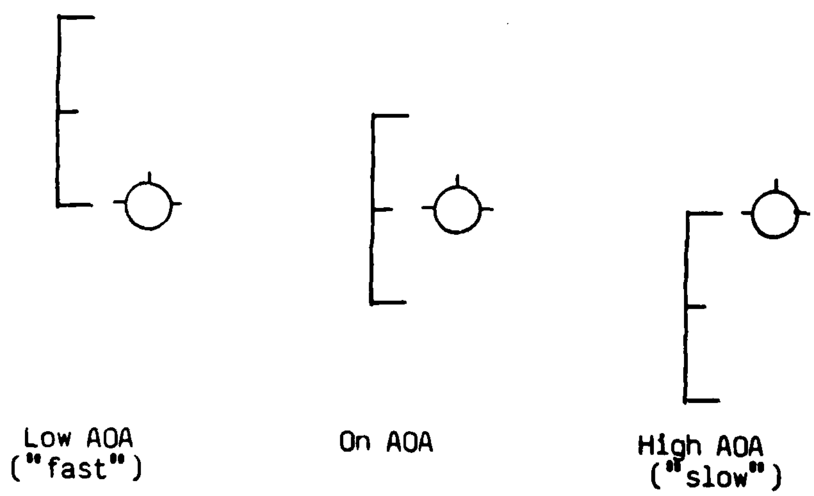
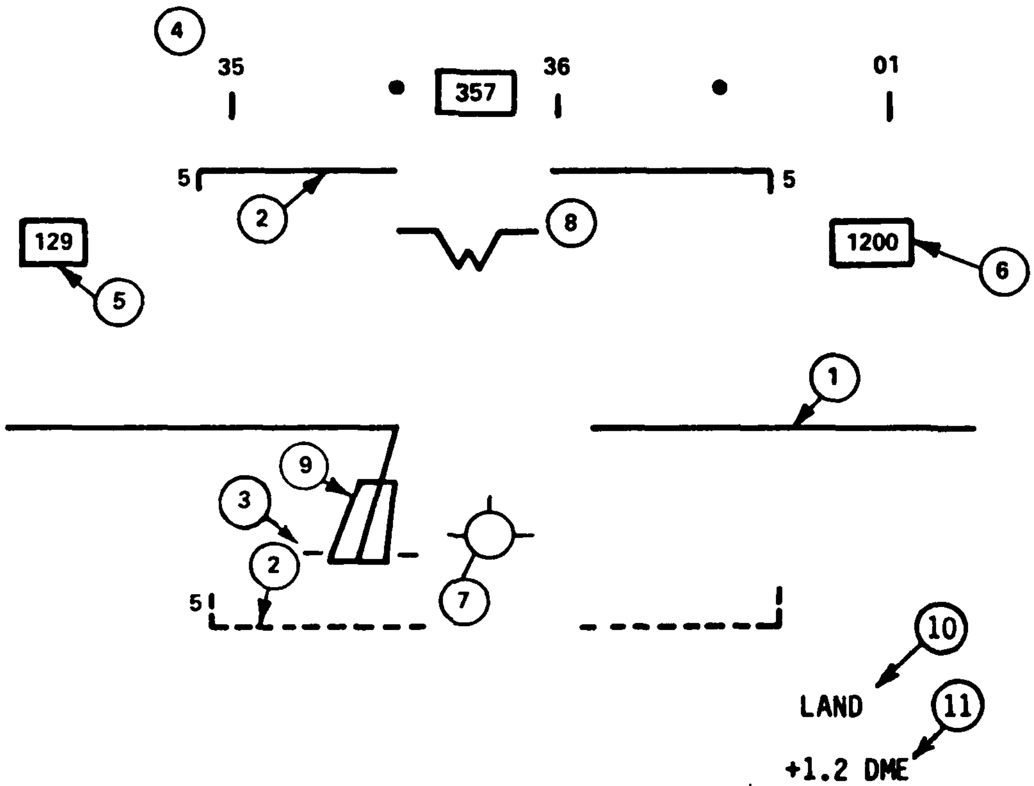


Figure 3

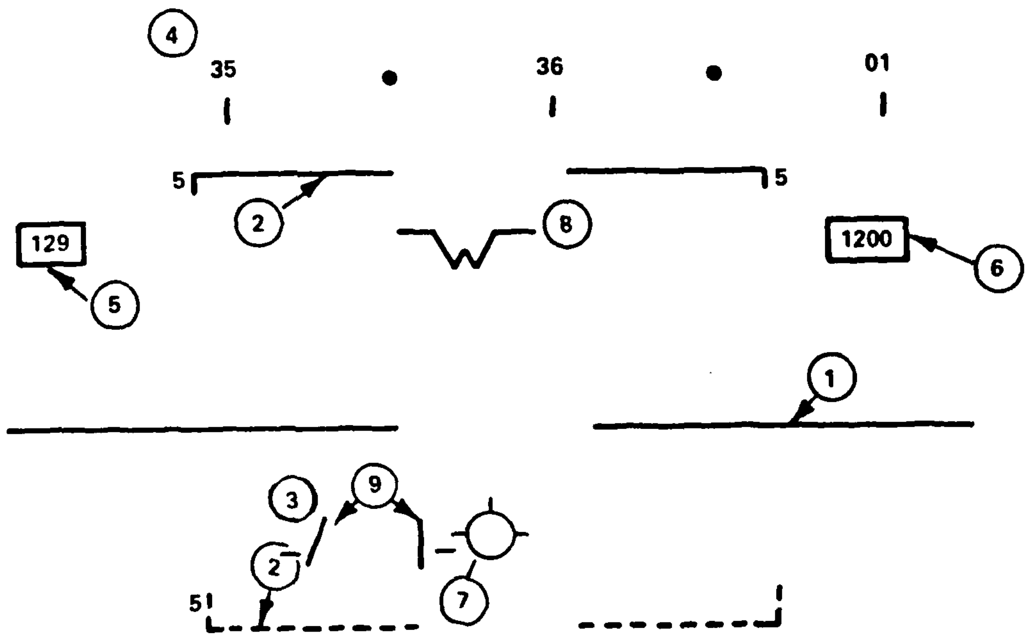
Angle of Attack Symbol



1. HORIZON LINE
2. PITCH LADDER
3. GLIDESLOPE ERROR
4. HEADING SCALE
5. INDICATED AIRSPEED
6. BAROMETRIC ALTITUDE
7. AIRMASS FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
8. WATERLINE (PITCH MARKER)
9. RUNWAY SYMBOL
10. MODE INDICATOR
11. DISTANCE, PARALLEL TO CENTERLINE, TO RUNWAY GPIP (NM)

Figure 4

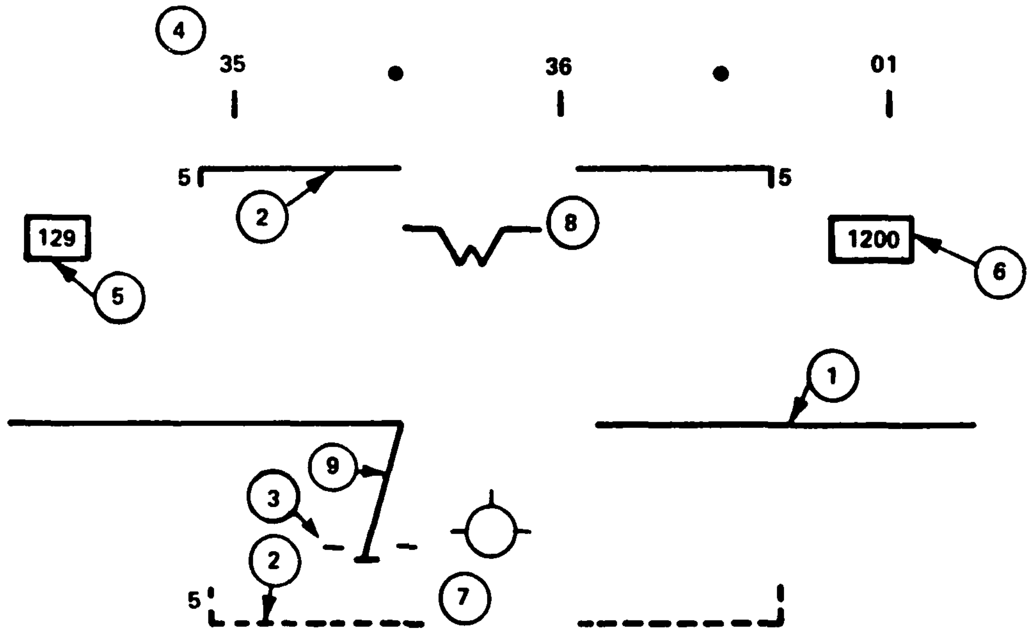
Runway Symbol A (Full Runway Outline)



1. HORIZON LINE
2. PITCH LADDER
3. GLIDESLOPE ERROR
4. HEADING SCALE
5. INDICATED AIRSPEED
6. BAROMETRIC ALTITUDE
7. AIRMASS FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
8. WATERLINE (PITCH MARKER)
9. RUNWAY SYMBOL B (Dimensions 2000' x 500')

Figure 5

Runway Symbol B (Sidelines Only)



1. HORIZON LINE
2. PITCH LADDER
3. GLIDESLOPE ERROR
4. HEADING SCALE
5. INDICATED AIRSPEED
6. BAROMETRIC ALTITUDE
7. AIRMASS FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
8. WATERLINE (PITCH MARKER)
9. RUNWAY SYMBOL (GPIP MARKER 175' IN WIDTH)

Figure 6

Runway Symbol C (Centerline Only)

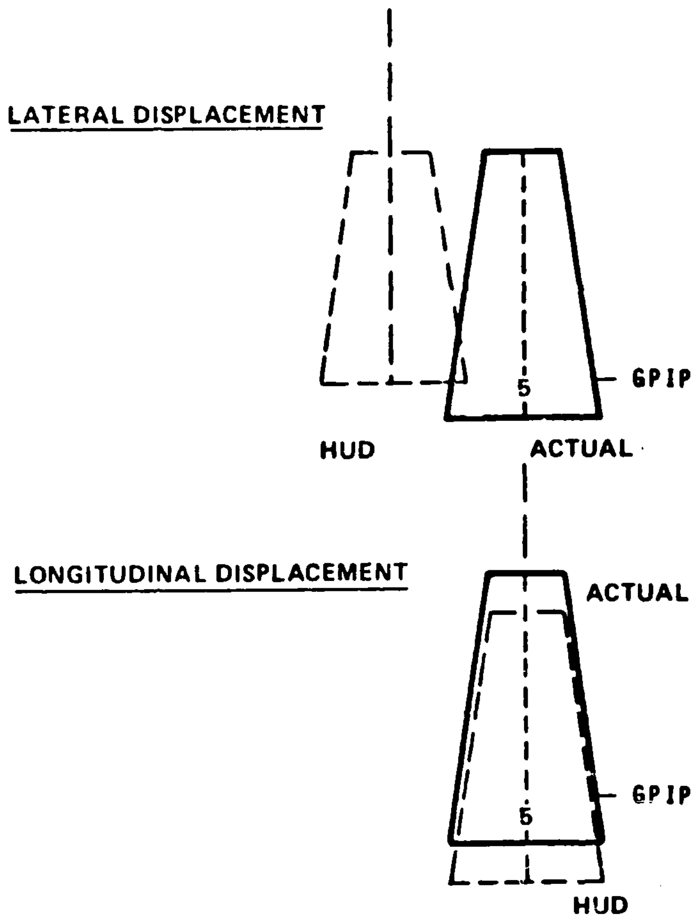


Figure 7

Intentional Errors Introduced

IV. CONDUCT OF THE EXPERIMENT

This experiment was performed using the USAF variable stability NT-33A aircraft. The evaluation procedures were tailored to the maximum extent possible to satisfy the objectives of the experiment.

A. Evaluation Pilots

Five evaluation pilots were used in the program. The experiment matrix was sized and planned for four evaluation pilots. The last piloting billet was thus shared by two pilots. Because of scheduling problems, the final evaluation totals were not evenly split among the four piloting slots.

B. Evaluation Procedures

Each evaluation pilot was briefed as to the objectives of the experiment and the head-up display formats that they would be flying. Particular attention was made to defining the display formats and features because some of these were new to the pilot or contradictory in sense or meaning to what they were accustomed. Informal comments and discussion with the evaluation pilots were solicited to examine their initial thoughts and reactions. They were later re-questioned after some flight experience regarding the displays and formats.

Informal pilot comments were also made during the course of the evaluation. Also, the pilots were asked to respond to a pilot comment card at the end of an evaluation (Table II). The intent of the comment card was to provide a common question-response series for each of the pilots and configurations. The pilot rating was made with reference to the Cooper-Harper pilot rating (CHPR) comment card (Figure 8, from reference 14).

Following the up-and-away evaluation which lasted 15 minutes on the average, the power approach evaluations were flown to either Niagara Falls Airport (Runway 28R) or Greater Buffalo International Airport (Runway 5 and 23).

C. Evaluation Tasks

For power approach configurations, the evaluation consisted of:

- The evaluation pilot (EP), flying on instruments (blue visor lowered), intercepted the ILS localizer.
- The evaluation pilot then flew the approach to decision height using the HUD as the primary flight reference.
- At decision height, the EP raised the blue visor and transitioned to a visual lineup and flare. A 20 ft AGL low approach was executed.
- Following the approach, aircraft control was passed to the safety pilot while the EP completed the pilot comments and CHPR.
- This sequence was repeated again with the EP performing a touch and go landing after breakout to visual.
- A third approach to landing could be performed at the discretion of the EP.

The decision height was varied as part of the experiment from a maximum of 200 ft AGL to 40 ft AGL. Typically, a 100 ft decision height was used.

Each approach was dictated as a must land situation. The evaluation pilots did not have any prior knowledge of the simulated configuration characteristics.

Integral to the Cooper-Harper rating scale is the definition of the required aircraft task and task performance standards. For the up-and-away evaluation, the aircraft's required task included all of the maneuvers and, hence, the rating for the configuration was based on performance in all maneuvers. The task performance standards were as defined in Table III.

Table I

EVALUATION PILOTS

Pilot Ident	Flying Time	Aircraft Background	HUDs Flown (a)
A	2700	Air-to-Air	F-15
B	2700	Transport	
C	2900	Air-to-Ground	F-16
D	14000	Transport	(b)
E	3600	Reconnaissance, Flight Test	A-7, A-10, F-15, F-16

(a) All evaluation pilots had flown HUD evaluations in simulators of various types.
(b) Pilot D had flown several HUD evaluations in flight.

Table II

PILOT COMMENT CARD

- Assign overall Cooper-Harper Pilot Ratings
- (Describe) effect of aircraft handling qualities on task performance and pilot workload:
- Up-and-away
  - simulated air-to-air
  - air-to-ground
  - acrobatics/unusual attitude recovery
- Powered Approach
  - approach
  - flare and landing/waveoff
- Was the display (overall) adequate for mission?
- Effect of display on task performance
- Effect of display on pilot workload
- Good feature(s) of display:
- Bad feature(s) of display:
- Were display problems/deficiencies a function of
  - task
  - flight conditions (VMC/IMC)
- Any factor in evaluation due to
  - turbulence?
  - others?
- Summary/overall comments
  - any change in rating

Table III

EVALUATION TASK PERFORMANCE STANDARDS

(POWER APPROACH)

Desired Performance Standards	Adequate Performance Standards
ILS Approach	
No PIO Glide slope and localizer errors less than 1/3 deg 50 % of task, less than 2/3 deg remainder of task.	Glide slope and localizer errors less than 1 deg for task.
Visual Landing	
No PIO Touchdown within 5 ft of center line and within 250 ft of aim point.	Touchdown within 5 ft of centerline and within 250 ft of aim point.

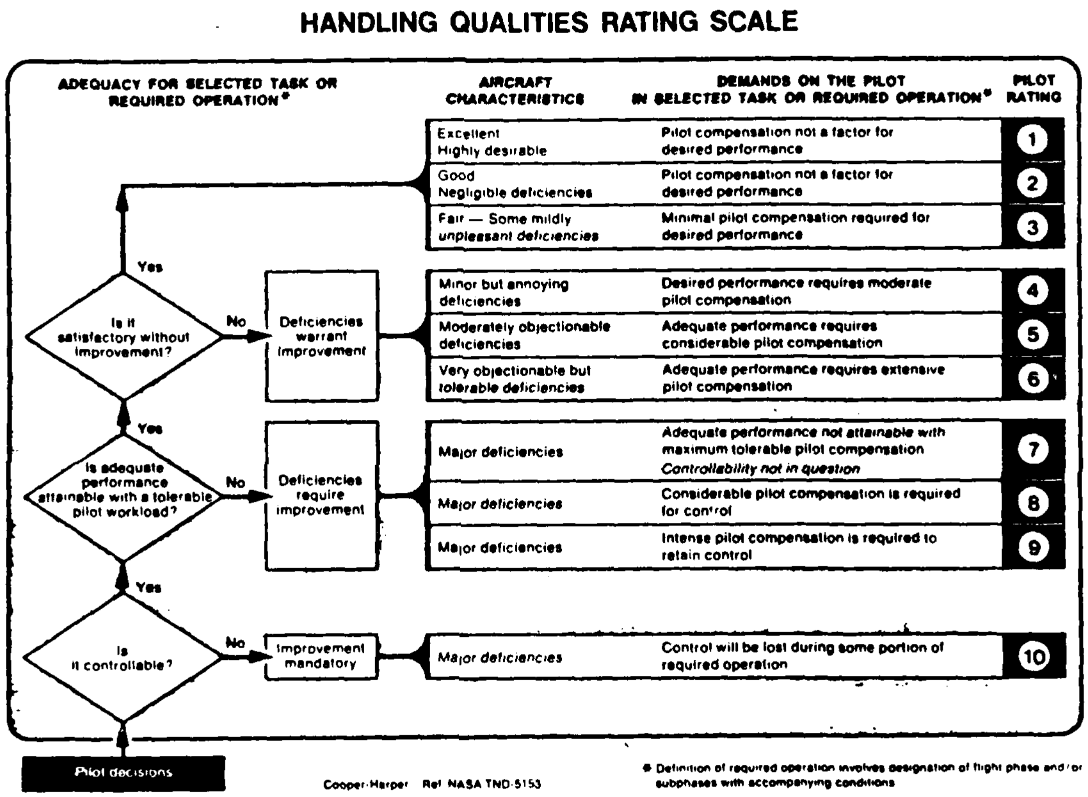


Figure 8

Pilot Rating Scheme (from Reference 14)

V. EXPERIMENT RESULTS

The results of this in-flight experiment are presented in this section with discussion and additional data correlations.

A Flight Program Summary

This flight program was performed in two phases. Phase I was flown in October 1985 and Phase II in January 1986. All flying originated from the Calspan Flight Research Facility in Buffalo, New York. The program consisted of 36 flights totaling 49.5 flying hours. 34 piloted evaluations were performed as part of this study. All of the evaluation pilots participated in the two flight phases with the exception of Pilot C who became unavailable for Phase II at the last moment due to a schedule conflict. The breakdown of flights and evaluations by pilot is shown in Table IV below.

Each of the pilots was given an orientation/practice evaluation to become familiar with the evaluation tasks and procedures.

B. Experimental Data

The experiment data consist of pilot rating, pilot comments, and task performance records. The task performance records include data recorded on an on-board AR-700 digital flight recorder and video taken by a camera mounted just aft of the HUD combining glass. The pilot comments for each evaluation are available in Reference (8).

Table V and Appendix I summarize the results.

1. Effect of Display Inaccuracies on Pilot Corrections

Intentional offsets of up to 1500 ft longitudinal and 200 ft laterally were flown. Heading deviations were scheduled for evaluation but were not flown because of time and funding constraints.

On each approach, the pilots were asked to place an event marker on the data at breakout. The event marker was activated by squeezing the trigger of the front cockpit centerstick. This placed a discrete voltage signal onto the digital onboard recorder and an "X" was drawn on the HUD. The event marker was used to investigate if any control mis-judgments were made in the face of runway misalignments. A typical time history is shown in Figure 9.

Examination of the approach time histories do not show any initial incorrect control inputs (initial control inputs in wrong direction). The pilot comments did not indicate any problems in picking up the real runway or transitioning to outside cues from the head-up display. One exception was on Pilot A's first flight (150 ft lateral offset, symbol C) where he noted difficulty in finding the real runway after breakout.

The various runways apparently did not dramatically influence the pilots transitioning to outside visual flight references. Aside from the single instance noted above, the pilots had no problems in the HUD-to-visual transition. HUD fixation was not reported to be a problem.

By virtue of the display design, intentional longitudinal errors short of the glidepath intercept point (GPIP) were more tolerable than errors past the GPIP. All runway symbols were reference to and drawn from the GPIP. The full runway display actually excluded the distance from the runway threshold to the glidepath intercept point; thus, an intentional error of up to approximately 1000' short of the GPIP would still draw the runway projection onto the actual runway surface. For longitudinal deviations past the GPIP, the primary difficulty facing the pilot at breakout is landing long or the requirement to go around.

2. Inter-Pilot Rating Comparison

An inter-pilot rating comparison cannot be made because of insufficient overlap between pilots in this task. Also, an apparent dilemma in the assignment of a CHPR in the face of intentional runway display offsets occurred. This dilemma involved questions such as:

- Was the display acceptable if it provided guidance to some incorrect/erroneous location?
- Did the display deficiencies warrant or require improvements?
- If it was possible to land the aircraft with desired performance despite some display offset at breakout, was the display deficient or did it need improvement?

Each of these questions was approached differently by each pilot and sometimes the pilots applied different standards on different approaches. The ratings were not consistent. The pilot comments are invaluable, however. Also, the ratings and comments contained personal, although unquantified, biases in terms of which synthetic runway they preferred.

3. Effect of Display Format

Three contact analog runway displays were mechanized. These varied significantly in terms of attractiveness and detail. This program represented the first exposure to a contact analog runway format for three of the pilots (Pilots A, B, and C). Few problems were noted by the pilots in adapting to the display format with the one exception being initial complaints of excessive pilot workload.

The pilots in their initial flights gave some critique to the landing display format in general. These initial thoughts are presented for completeness in terms of a lessons learned section defining the HUD format deficiencies. These deficiencies were not remedied for this program nor do they significantly affect the results. (Comments regarding the air mass flight path for the power approach task have already been presented and are not repeated here). The potential display deficiencies were:

- The display lacked a bank angle index. Four pilots felt that a bank index was required for the power approach task (None felt it was required for the up-and-away flight tasks).

- The display lacked rate information. Pilot D continually bemoaned the absence of explicit rate parameters such as airspeed rate or altitude rate.

- Angle of attack bracket was drawn with respect to the waterline and to the velocity vector. When the velocity vector was uncaged in azimuth, the angle of attack bracket and velocity vector were not necessarily beside each other. This was an annoyance because both symbols were treated as primary control parameters. Any significant displacement between the two symbols increased the pilot's scan pattern and attendant pilot workload.

Four pilots clearly preferred Symbol A (the full runway display). This runway display was felt to provide the best perceptual cues in the approach.

Symbol B (sidelines only display) was not well received primarily because of its short runway sidelines (2000 ft) and width (500 ft). The short runway length was felt to limit the perspective cues for line-up that were inherent to the other symbols. For the 2nd phase of evaluations, the width of Symbol B (Symbol B') was reduced to 250' and the symbol's acceptance was improved. One good feature of Symbol B was found to be that the runway sidelines formed a natural box for which to fly and keep the flight path inside of on the approach. This was felt to be a

nice feature. Deviations of the flight path outside the box were easily noted, thus providing a strong cue feedback to the pilot.

Symbol C was sometimes preferred over Symbol B as the second choice behind Symbol A. The approach course line up was felt to be strong for this symbol, as one might expect from its characteristics. Also, glidepath deviations could be easily picked out because of the spareness of the display.

The results of this program are certainly valid with two caveats. First, intentional runway obstructions were not attempted to test whether the pilot's were actually experiencing HUD fixation. It has been previously reported that in ground-based simulations, pilots were unaware of runway obstructions during flight with a HUD-equipped aircraft(15). For instance, pilots did not see aircraft taxiing onto the active runway during an approach to landing. It is doubtful that the pilots would have had any problems seeing obstructions in this experiment. The visual cues in this program are real and the visibility conditions were typically excellent unlike what may be presented during ground-based simulation experiments. Also, the blue/amber IMC simulation may influence this result. In operation, the runway displays and any symbol inaccuracy would become critically important in an actual IMC situation. In the blue/amber simulation, IMC flight is conducted up to a VMC/full daylight breakout. No shades of grey or low visibility conditions were simulated. It may be the case that HUD fixation during the transition from inside to outside visual cues and the identification of runway display errors are hindered more under low visibility conditions.

4. Effect of Crosswinds

Four evaluations were flown for this task in high crosswind environments and, in each case, poor ratings were given because of the field-of-view limitations. The rating degradation was 1 to 2 CHPRs. In the presence of a crosswind, the contact analog runway display will be offset from the center of the HUD. The NT-33 HUD has an approximately 16 deg instantaneous lateral FOV or +/-8 deg from center. For crab angles of greater than 7 deg, the runway display symbology can be blanked because of FOV limitations. When this occurred, the evaluation pilots had to transition to alternative landing guidance in the approach. Unfortunately, for large crab angles, no landing guidance at all is provided in the HUD. This is a limitation of the current DEFT design and it was not altered for this program. This issue and its solution were not a part of the experiment. These crosswind evaluations are excluded from the analytic discussion since FOV was not a specific experiment variable.

5. Interaction with Display Dynamics Experiment

The pilot comments, as delay was added to the display, note increased and possibly annoying "bouncing" of the display. The experimentally added delay was such that the entire display was

uniformly delayed. Of particular concern was the movement of the conformal runway which provided the landing guidance information. The pilot rating and flying qualities evaluation were decided by whether the pilot could compensate for the bouncing of the display or whether the bouncing deficiency warranted or required improvement. The pilot compensation for the bouncing was primarily to estimate the mean position of HUD symbols through their range of movement and attempt to control that movement. It was not the case that controllability problems occurred. At the highest time delay values, the pilots were seriously questioning the validity of the display and knowing that the movement on the display was not caused by turbulence or control inputs. In this case, the pilots ceased to track the velocity vector and runway display tightly.

6. Additional Observations

In these evaluations, a contact analog runway symbology was used as the baseline HUD display. For the majority of the evaluation pilots, it was their first exposure to this type of display. In general, the runway display symbology was found to be an effective, safe, and natural method for landing guidance. The pilot comments were virtually unanimous in indicating acceptance of the display. From informal comments, the only major deficiency of the display format was the air mass velocity vector. The majority of pilots expressed a desire for an inertial velocity vector. This desire may have also been prompted by the lack of a track angle marker for the air mass velocity vector. The inertial velocity vector may not have been necessary if a track marker was provided.

The conformal runway display (even without any added display delay) was sometimes thought to be unrealistic in its movement, particularly in response to control inputs or turbulence. The conformal display was said to bounce excessively and be overly sensitive. In actuality, the movements of the runway display were not excessive nor inaccurate. The displayed runway position and its relative motion were an accurate representation of the outside world. The pilot's observations were of a perceptual phenomenon. The runway outline display is projected against a virtual black (IMC) background. This display provides the pilot a relatively small foveal viewport to the outside world. Thus control movements or turbulence which cause aircraft attitude changes create large displacements relative to the total FOV of the HUD. This perception was noted primarily on the first flights and subsided as experience grew. Certainly learning effects played a role in adapting to this display.

The effect of such a small FOV on approach to landing using a periscope showed a tendency for pilots to mis-judge the approach and fly consistently low(16). No such effect was noted in this study.

The different reference frames between the inertial and the air mass velocity vector were a significant factor. In numerous instances, the nominal air mass velocity vector was criticized because of its inability to depict precisely the flight path in relation to the HUD runway display. The pilots did not feel that they were getting the help from the display that was possible because of the need to correct explicitly for wind variations. This situation was particularly acute for crosswind situations, where it was necessary to hold the velocity vector, some lateral distance from the "no-wind" aimpoint on the runway display. This situation is alleviated totally with an inertial velocity vector and might have been eased by the addition of a track marker to the air mass referenced display.

Table IV

EVALUATION SUMMARY

Pilot Identification	Flights	Evaluations		
		Task A(a)	This Study	Total
A	10	38	13	51
B	7	26	5	31
C	4	19	6	25
D	4	5	8	13
E	3	8	2	10
Total	28	96	34	130

(a) Dynamic Response Study (8)

Table V

SYMBOL ACCURACY EVALUATION SUMMARY (a)

Offset		Symbol A		Symbol B		Symbol C		Average	
No Offset		8	3.1	3	4.5			11	3.5
Lat. Off set	150 ft	1	6.0			2	4.5	3	5.0
	200 ft	1	4.5	4	5.1	3	5.3	8	5.1
Long. Off-set	-500 ft	1	4.0					1	4.0
	-1000 ft			2	2.8			2	2.8
Note (b)	-1500 ft	2	2.5	1	4.0	1	5.0	4	3.5
	+1000 ft	2	5.0			3	4.2	5	4.5
Summary		15	3.9	10	4.4	9	5.8	34	4.3

(a) Key: Number of evaluations Average Rating
(b) Minus denotes short of GPIP; Plus denotes past GPIP

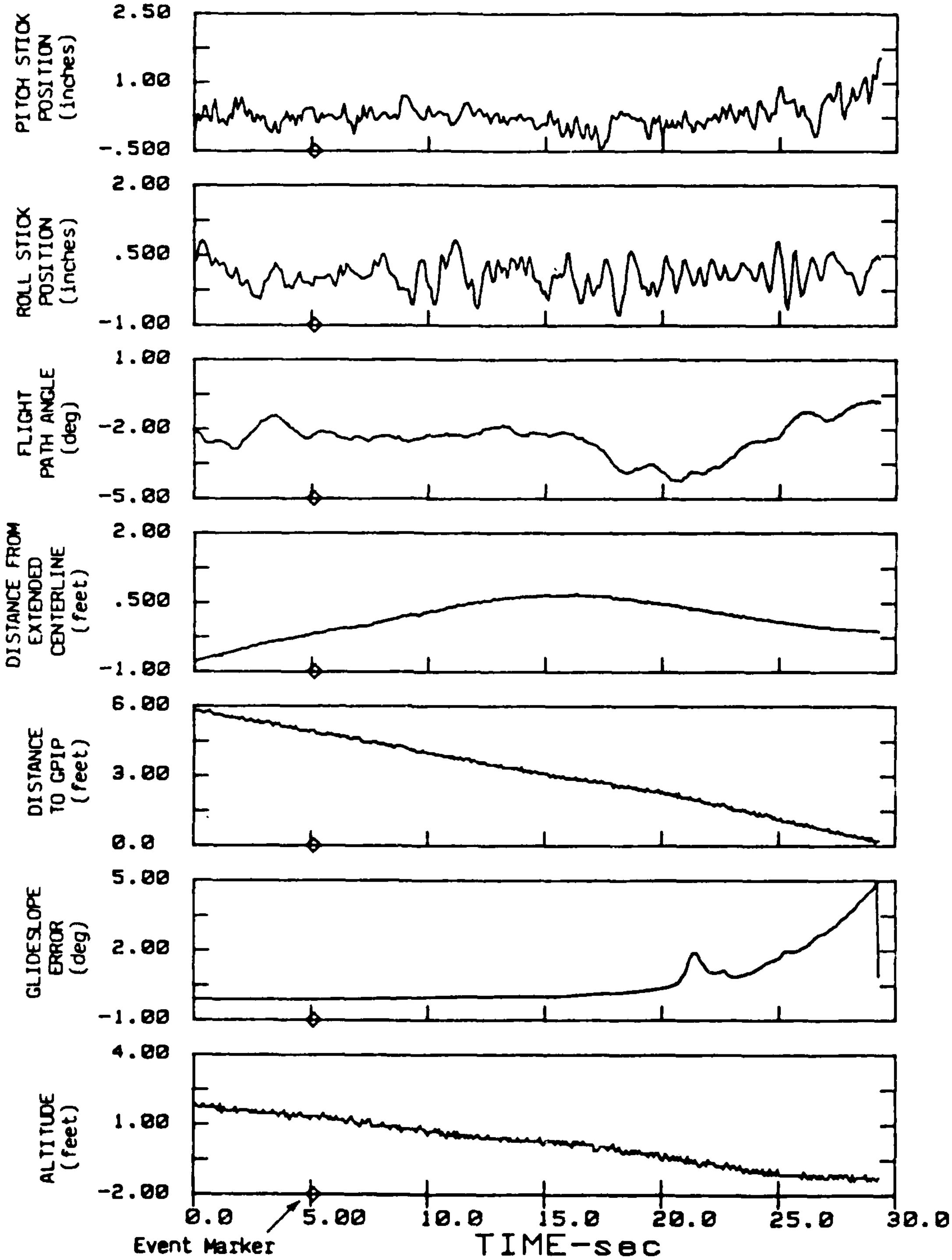


Figure 9

Approach and Landing Time History Example

VI. CONCLUSIONS

An in-flight investigation of the effect of head-up display symbol accuracy requirements was performed using the USAF NT-33A aircraft. Up to 200 ft lateral offsets and 1500 ft longitudinal deviations were flown. The results of this study suggest that:

- These deviations were clearly evident at visual breakout and at least adequate landing performance was attainable.
- Control activity at breakout did not indicate any problems or errors in judgment in the transition from IMC to VMC. Only one instance was there a problem noted in visually acquiring the real runway. This instance was the first approach by one evaluation pilot.
- The runway perspective symbols was easily flown by the evaluation pilots.
- The evaluation pilots preferred the complete runway outline with the centerline/threshold symbol rated second.

Several experimental factors may have influenced these results. Among these are the unrealistic transition from total instrument conditions to total visual conditions with good visibility. The effect of visual conditions with very limited visibilities was not simulated.

The conclusions do not support the MD-80 experience which indicate a highly realistic runway symbol is overly compelling and can cause a pilot to ignore real world cues. They also do not support the observations made during the MARS HUD studies in which the pilots ignored real world cues and flew HUD symbols.

They do support early HUD simulations in which pilots tended to fly real world cues and not erroneous HUD symbols.

This may be a result of the evaluation pilots distrust of the air mass velocity vector coupled with the knowledge that the HUD symbols were being degraded.

The results indicate that accurate position information is not a requirement for a HUD to be useful during an ILS approach. That is, an inertial navigation system is not required. However, based on earlier experience, accurate pitch, roll, and heading data is essential for a usable HUD. For this reason, a inertial quality gyro platform (AHRS) will probably be required.

It does appear that the use of Cooper-Harper Pilot Ratings (CHPR) for display evaluations does not supply enough data to adequately rate and rank the various symbologies. Future flight data cards require display specific questions. The CHPRs alone can be masked by handling issues. In the present study, CHPRs were necessary to deal with the display dynamics portion of the flight. In this study, unfortunately, we elected not to ask enough of the right questions concerning the effect of the various formats.

By their nature, CHPRs are mission-related. In display symbology research, the display may be intentionally inadequate for the mission (as in this study). This virtually guarantees ratings of 4, 5, and 6.

VII. RECOMMENDATIONS

The following recommendations can be made:

- The use of an inertial navigation system is not required for future HUDs. Other studies do indicate that inertial quality gyroscopic platforms will be required for proper attitude sensing (particularly for a heading reference).

- A perspective runway symbol is more than adequate for ILS approaches.

- A full perspective runway symbol (Symbol A) is preferred. Based on previous HUD experience in poor visibility, the use of a less compelling display (Symbol B) is recommended for airplanes not equipped with inertial navigation systems.

- Future studies of this type should develop means to simulate restricted visibility. One approach might be to have the evaluation pilot wear two thicknesses of blue and remove only one. If the intensity of the blue were adjusted properly, a faint view of the external world would be available.

- Future studies evaluating variations of a baseline display should use display specific questionnaires designed to point out the differences being examined. Handling qualities ratings may not yield sufficient information.

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APPENDIX I

SYMBOL ACCURACY EVALUATION RESULTS (a)

Offset		Symbol A	Symbol B	Symbol C	ILS Needle
No offset		A: 3 (D) A: 5 (D) B: 3 (D) D: 4 (D) D: 3 (E) C: 3 (T) D: 3.5(T)	A: 5 (T) -------- A: 3.5(T) D: 5 (T) (b)		A: 2 (D)
Lateral Offset	100 ft				
	150 ft	C: 6 (D)		A: 3 (D) B: 6 (D)	
	200 ft	A: 3 (D) B: 6 (D)	C: 5.5(D) B: 7 (T) C: 4 (T) D: 4 (T)	A: 4.5(D) C: 7 (D) D: 4.5(E)	
Longitudinal Offset	-500 ft	A: 4 (T)			
	-1000 ft		A: 3 (D) D: 2.5(D)		
	-1500 ft	A: 2 (D) B: 3 (D)	C: 4 (D)	D: 5 (D)	
	+500 ft				
	+1000 ft	A: 5 (D) D: 5 (D)		C: 3 (D) A: 5 (T) D: 4.5(T)	
Note (c)	+1500 ft				

(a) Key: Pilot: Pilot Rating (Configuration)
(b) Below line symbols were B'
(c) Minus denotes short of GPIP; Plus denotes past GPIP

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